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Solar Radiation Alert System (Revised 30 May 2008)

Kyle Copeland¹
Herbert H. Sauer²
Wallace Friedberg¹

¹Civil Aerospace Medical Institute
Federal Aviation Administration
Oklahoma City, OK 73125

²National Geophysical Data Center
National Oceanic and Atmospheric Administration
Boulder, CO 80305

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16. Abstract The Solar Radiation Alert (SRA) system continuously evaluates measurements of high-energy protons made by instruments on GOES satellites. If the measurements indicate a substantial elevation of effective dose rates at aircraft flight altitudes, the Civil Aerospace Medical Institute issues an SRA via the National Oceanic and Atmospheric Administration Weather Wire Service. This report describes a revised SRA system. SRA issue-criteria remain the same but significant improvements have been made in the calculations. The solar proton fluence to effective dose conversion coefficients have been recalculated using 2007 recommendations of the International Commission on Radiological Protection and the latest release of the Monte Carlo transport code, MCNPX 2.6.0. The shape of the <10 MeV secondary neutron spectrum is now accounted for down to 100 eV. The flux correction based on spectral index has been revised to smooth the flux spectrum of solar protons. Estimates of the >605 MeV spectral shape have been improved by the addition of correction factors for the differential interpretation of the >700 MeV integral flux channel. Estimates of galactic cosmic radiation background count rates in the GOES data are now median rather than mean values. Estimated solar cosmic radiation dose rates are about 10 times higher than those made using the previous version of the SRA system.					
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SOLAR RADIATION ALERT SYSTEM

INTRODUCTION

Background

During air travel, aircraft passengers and crew are usually exposed to ionizing radiation at higher dose rates than members of the general population. The principal ionizing radiation for air travelers is galactic cosmic radiation, a main source of which is supernovae (exploding stars). Occasionally, a disturbance in the Sun leads to a large flux of solar protons with sufficient energy to penetrate Earth's magnetic field, enter the atmosphere, and increase ionizing radiation levels at aircraft flight altitudes (geopotential altitudes are reported). For a primer on aircrew exposure to ionizing radiation see Reference 1.

Overview

The Federal Aviation Administration (FAA) has in operation a system for continuous evaluation of proton flux measurements made by instruments on Geosynchronous Operational Environmental Satellites (GOES). The system is illustrated in Figure 1. At present, the primary data source is GOES-11; GOES-10 measurements are used if there is a problem obtaining data from GOES-11. If measurements indicate the likelihood of a substantial elevation of ionizing-radiation levels at aircraft flight altitudes at polar latitudes (locations with an effective cutoff rigidity of ~ 0 MV (2)), the FAA's Civil Aerospace Medical Institute (CAMI) issues a Solar Radiation Alert (SRA) to the National Oceanic and Atmospheric Administration Weather Wire Service (NWWS) (3).

The specific criteria for issuance of an SRA is that the estimated effective dose rate induced by solar protons at 70,000 ft equals or exceeds 20 microsieverts per hour ($\mu\text{Sv/h}$) for each of three consecutive 5-minute periods. Because of the potential for a delay of 3-20 minutes in communication processes and the three 5-minute periods, notification of the start of SRA conditions may be 18-35 minutes after the start of the first 5-minute period. The SRA is canceled when the average effective dose rate at 70,000 ft is less than 20 $\mu\text{Sv/h}$ for six consecutive 5-minute periods.

Revisions Since the Earlier Version

This report replaces Office of Aerospace Medicine report DOT/FAA/AM-05/14 (4) describing the previous version of the FAA SRA system. Significant changes include:

(a) Table 1 has been revised to reflect significant improvements: particle fluences in the atmosphere have been recalculated using the most recent release of the Monte Carlo transport code, MCNPX 2.6.0 (5). Effective dose has been recalculated based on the 2007 recommendations of the International Commission on Radiological Protection (6) with the shape of the <10 MeV secondary neutron spectrum accounted for down to 100 eV. Also, the table values have been restated in terms of dose per unit fluence of particles entering the atmosphere, rather than unit fluence measured at the satellite.

(b) Step 5 has been revised to smooth the flux spectrum of solar protons. Step 8 has been revised to reproduce the measured flux by altering the spectral intensity rather than the spectral-hardness index. A new Step 10 has been added to convert from GOES flux to flux entering the atmosphere.

(c) Estimates of spectral hardness and intensity involving data from the High-Energy Proton and Alpha Detector (HEPAD) have been improved through the addition of correction factors for the differential interpretation of channel P11 (Table 3).

(d) Estimates of galactic cosmic radiation "background" count rates in the GOES data are median rather than mean values.

The net result of the revisions, combined with bug fixes in the source code, is considerably higher dose rates at all altitudes. As an example, Figure 2 shows estimates made for 20 January 2005 using both versions.

SRA messages

Six different message types are issued to the NWWS (3): Test, Alert, Alert Update, Alert Cancellation, Service Suspended, Service Resumed. A Test message is sent every day at 1500 Coordinated Universal Time (UTC), unless conditions indicate an Alert, Alert Update, or Alert Cancellation message should be sent. An Alert message is sent when the criteria for an SRA is met. After the Alert message, Alert Update messages are sent every 5 minutes until the conditions indicate that the SRA should be cancelled. The Alert Cancellation message is then sent. A Service Suspended message is sent when the system cannot obtain up-to-date GOES data. Data outages can occur during GOES eclipse seasons and because of communications trouble between SWPC and

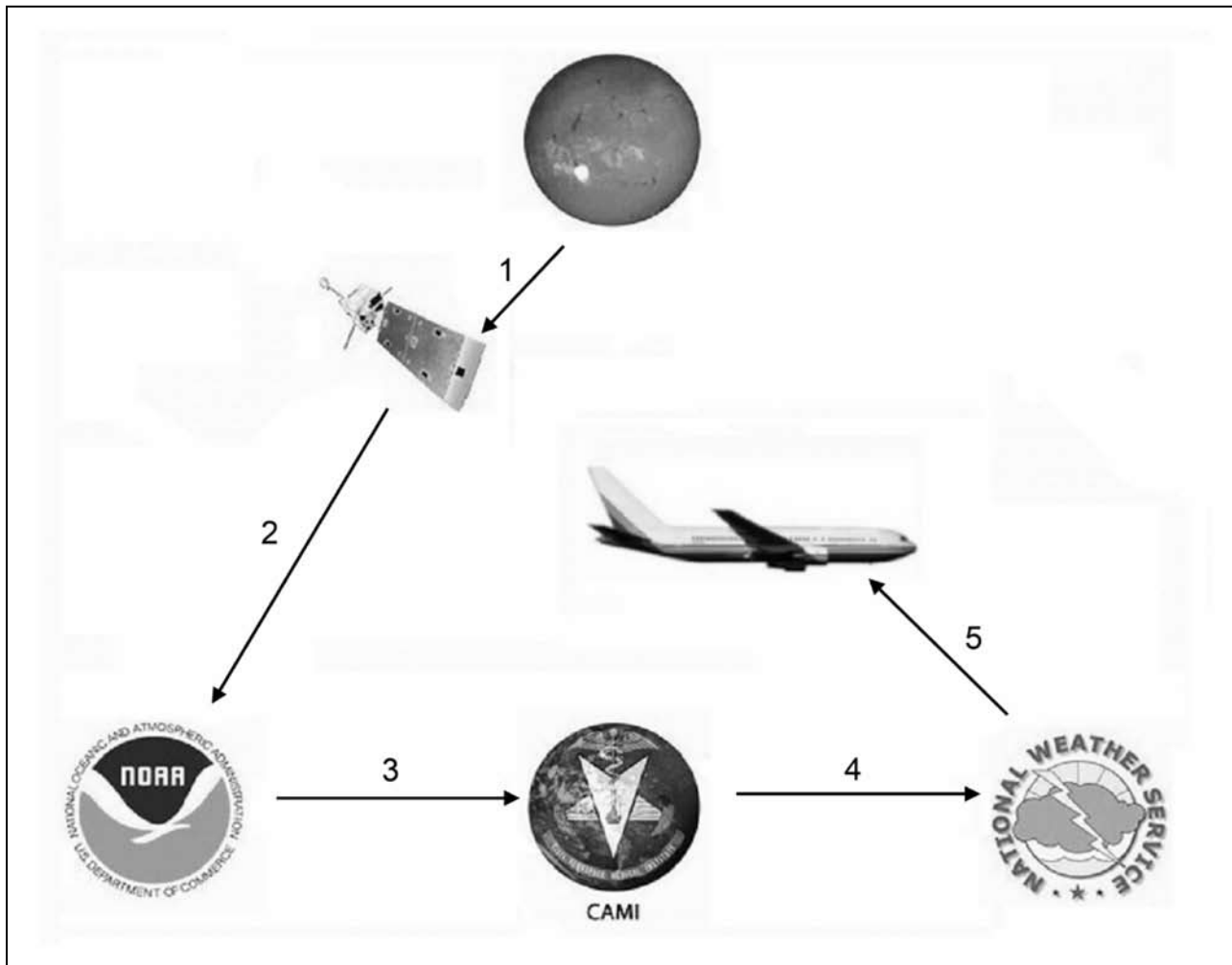


Figure 1. Solar Radiation Alert system: (1) Occasionally, a disturbance in the Sun (solar flare, coronal mass ejection) leads to a large flux of high-energy particles in the vicinity of the Earth. (2) Instruments on a GOES satellite continuously measure the radiation, and the information is transmitted to NOAA. (3) From there it is sent to CAMI. A computer at CAMI analyzes the measurements. (4) If the measurements indicate the likelihood of a substantial elevation of ionizing radiation levels at aircraft flight altitudes, a Solar Radiation Alert is issued to the NOAA Weather Wire Service. Estimated effective dose rates for 30-, 40-, 50-, 60-, and 70-thousand feet are included and updated at 5-minute intervals for the duration of the alert. (5) The National Weather Service distributes alerts and updates via the NOAA Weather Wire Service and the Internet.

Table 1. Effective dose per unit incident fluence, $\Delta(R,H)^a$, to an adult at altitude (H), from incident exoatmospheric protons of rigidity (R)

Rigidity (R) MV	Altitude (H) ^b				
	-50 ft	9722 ft	19,588 ft	29,378 ft	39,197 ft
183.5	1.00×10^{-16}	1.00×10^{-16}	1.00×10^{-16}	1.84×10^{-11}	4.52×10^{-10}
245.6	1.00×10^{-16}	1.00×10^{-16}	3.08×10^{-13}	5.69×10^{-11}	1.39×10^{-9}
329.7	1.00×10^{-16}	1.00×10^{-16}	4.51×10^{-13}	2.76×10^{-10}	8.16×10^{-9}
444.6	1.00×10^{-16}	4.42×10^{-12}	5.03×10^{-10}	1.77×10^{-8}	2.65×10^{-7}
604.4	6.31×10^{-10}	6.05×10^{-10}	2.03×10^{-8}	3.39×10^{-7}	2.69×10^{-6}
832.7	2.44×10^{-9}	7.11×10^{-8}	8.83×10^{-7}	5.89×10^{-6}	2.45×10^{-5}
1171.	2.43×10^{-8}	7.37×10^{-7}	7.21×10^{-6}	3.78×10^{-5}	1.32×10^{-4}
1696.	2.17×10^{-7}	4.62×10^{-6}	3.79×10^{-5}	1.93×10^{-4}	6.36×10^{-4}
2549.	8.26×10^{-7}	1.49×10^{-5}	1.11×10^{-4}	4.70×10^{-4}	1.24×10^{-3}
3991.	1.92×10^{-6}	3.54×10^{-5}	2.53×10^{-4}	9.84×10^{-4}	2.38×10^{-3}
4848.	2.77×10^{-6}	4.89×10^{-5}	3.37×10^{-4}	1.27×10^{-3}	3.01×10^{-3}
6494.	5.82×10^{-6}	8.75×10^{-5}	5.48×10^{-4}	1.93×10^{-3}	4.19×10^{-3}
10,898.	3.14×10^{-5}	2.07×10^{-4}	1.06×10^{-3}	3.45×10^{-3}	7.13×10^{-3}
18,695.	9.98×10^{-5}	4.61×10^{-4}	2.05×10^{-3}	6.14×10^{-3}	1.18×10^{-2}
20,917.	1.02×10^{-4}	5.54×10^{-4}	2.36×10^{-3}	6.75×10^{-3}	1.25×10^{-2}
32,545.	2.35×10^{-4}	9.41×10^{-4}	3.65×10^{-3}	9.98×10^{-3}	1.81×10^{-2}
Rigidity (R) MV	Altitude (H) ^b				
	48,977 ft	58,749 ft	68,511 ft	78,260 ft	
183.5	4.18×10^{-9}	1.91×10^{-8}	5.22×10^{-8}	9.68×10^{-8}	
245.6	1.52×10^{-8}	7.82×10^{-8}	2.21×10^{-7}	4.25×10^{-7}	
329.7	9.16×10^{-8}	4.48×10^{-7}	1.23×10^{-6}	2.33×10^{-6}	
444.6	1.64×10^{-6}	5.39×10^{-6}	1.16×10^{-5}	1.89×10^{-5}	
604.4	1.11×10^{-5}	2.86×10^{-5}	5.36×10^{-5}	8.15×10^{-5}	
832.7	6.87×10^{-5}	1.43×10^{-4}	4.38×10^{-4}	1.78×10^{-3}	
1171.	5.30×10^{-4}	1.37×10^{-3}	1.81×10^{-3}	1.88×10^{-3}	
1696.	1.25×10^{-3}	1.80×10^{-3}	2.13×10^{-3}	2.26×10^{-3}	
2549.	2.20×10^{-3}	2.97×10^{-3}	3.36×10^{-3}	3.41×10^{-3}	
3991.	3.91×10^{-3}	4.93×10^{-3}	5.29×10^{-3}	5.17×10^{-3}	
4848.	4.84×10^{-3}	6.01×10^{-3}	6.37×10^{-3}	6.16×10^{-3}	
6494.	6.32×10^{-3}	7.47×10^{-3}	7.62×10^{-3}	7.17×10^{-3}	
10,898.	1.00×10^{-2}	1.11×10^{-2}	1.07×10^{-2}	9.62×10^{-3}	
18,695.	1.57×10^{-2}	1.65×10^{-2}	1.53×10^{-2}	1.34×10^{-2}	
20,917.	1.62×10^{-2}	1.69×10^{-2}	1.56×10^{-2}	1.36×10^{-2}	
32,545.	2.30×10^{-2}	2.31×10^{-2}	2.08×10^{-2}	1.76×10^{-2}	

^a $\mu\text{Sv}/(\text{incident proton}/\text{cm}^2)$

^b Geopotential altitude converted from atmospheric depth (11).

Table 2. Conversion factors (k , k') and characteristic rigidities ($R_{P[j]}$ in MV) (7)

Channel	Conversion factor k ^a	Conversion factor k' ^b	Characteristic rigidity ($R_{P[j]}$) ^c
P4	4.64	22.25	225.1
P5	15.5	43.04	338.2
P6	90.	252.8	563.9
P7	300.	1210.	950.0
P10	162.	175.6	1225.
P11	1565. ^d	1103.	1700.

^a k : counts/(particles/(cm²•sr•MeV))

^b k' : counts/(particles/(cm²•sr•MV))

^c The characteristic rigidity is a weighted average rigidity, where the weighting depends on the instrument sensitivity across the width of the channel and the assumed spectral shape.

^d k : counts/(particles/(cm²•sr))

Table 3. Spectral-hardness index correction factors (s) for protons (7) ^a

Spectral-hardness index, γ	Channel					
	P4	P5	P6	P7	P10	P11
	Spectral-hardness index correction factor					
≤ 0	1.0000	1.0000	1.0000	1.0000	1.0000	0.289
1	0.9565	0.9775	0.9733	0.9300	0.9968	0.289
1.5	0.9171	0.9562	0.9483	0.8675	0.9936	0.289
2	0.8777	0.9350	0.9233	0.8050	0.9904	0.513
3	0.7751	0.8764	0.8553	0.6502	0.9808	0.812
4	0.6609	0.8060	0.7753	0.4913	0.9683	0.962
5	0.5458	0.7284	0.6888	0.3485	0.9529	1.01
6	0.4380	0.6476	0.6011	0.2329	0.9348	1.00
7	0.3428	0.5674	0.5161	0.1473	0.9142	0.948
8	0.2623	0.4904	0.4366	0.08856	0.8914	0.874
9	0.1969	0.4186	0.3645	0.05089	0.8666	0.789
≥ 10	0.1453	0.3533	0.3006	0.02811	0.8400	0.702

^a Intermediate correction factors are obtained by linear interpolation.

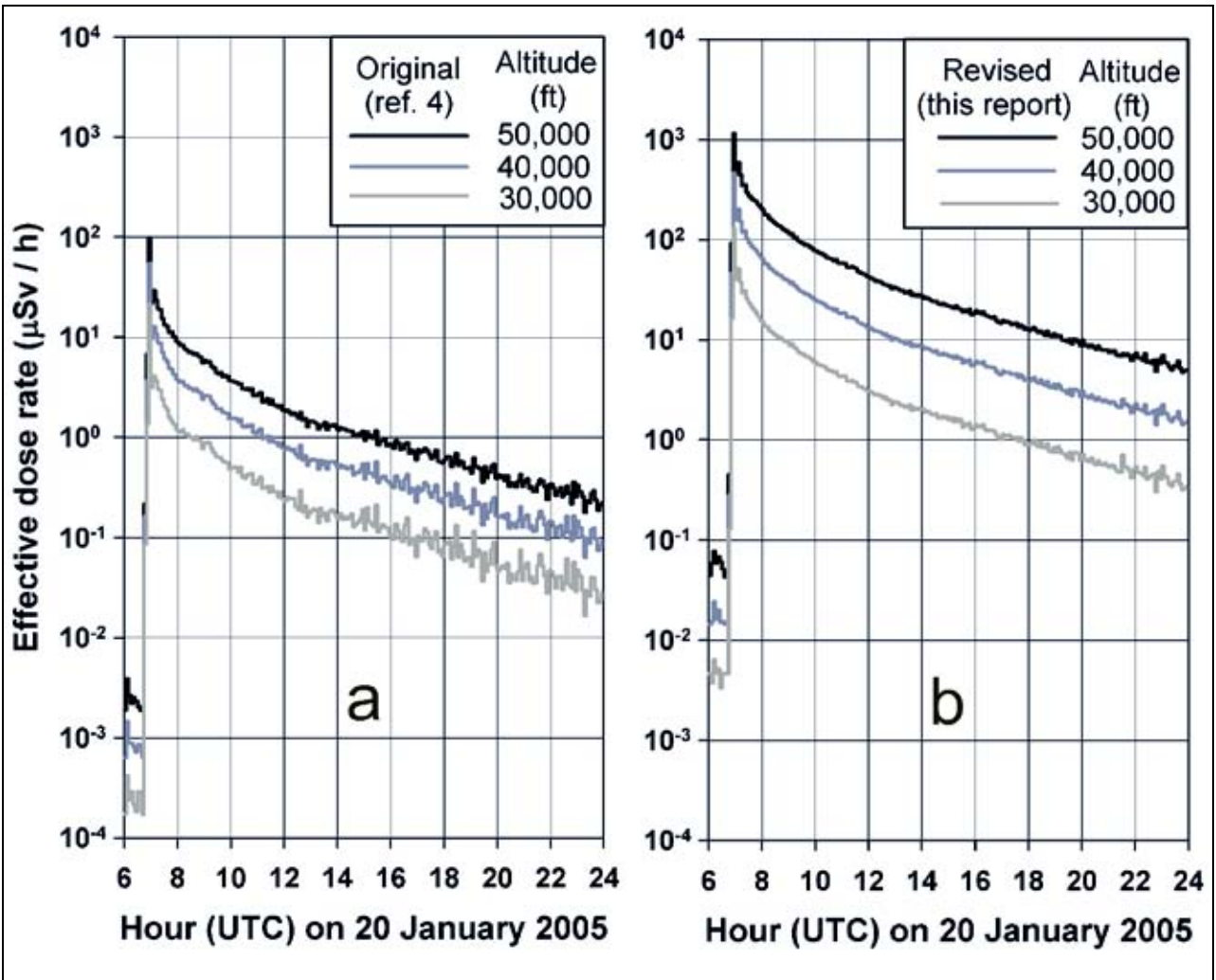


Figure 2. (a) Original SRA system estimates of effective dose rate on 20 January 2005, during the solar proton event of 16 January 2005; (b) Revised SRA system estimates of effective dose rate on 20 January 2005, during the solar proton event of 16 January 2005.

Table 4. Rigidity limits (in MV) for differential flux spectra

Flux spectrum (<i>i</i>)	1	2	3	4	5	6
Lower rigidity, $R_{i,lower}$	137	338	564	950	1225	1343
Upper rigidity, $R_{i,upper}$	338	564	950	1225	1343	See Step 9

CAMI. Information given with Alert and Alert Update messages includes:

- (a) Estimated effective dose rates from solar cosmic radiation in $\mu\text{Sv/h}$, based on 5-minute averages, at altitudes of 30-, 40-, 50-, 60-, and 70-thousand feet.
- (b) Estimated risk that the equivalent dose to the conceptus will exceed $500 \mu\text{Sv}$ at 40-, 50-, and 60-thousand feet in a 10-hour exposure.
- (c) Effective doses for the previous 1, 3, 5, and 10 hours at 40-, 50-, and 60-thousand feet.

A sample of each type of message issued by the system is in Appendix A. SRA system related messages can be identified in three ways:

- (a) The Advanced Weather Interactive Processing System (AWIPS, 7) identifier is ALTPAV.
- (b) The Space Weather Message Code is ALTPAV.
- (c) The World Meteorological Organization (WMO) header is WOX50 KWNP.

Subscribers to the NWWS receive SRA messages as part of the stream of weather related messages transmitted through the NWWS. Recent SRA and other space weather related messages are also available at the National Weather Service Web site: www.weather.gov/view/national.php?prodtype=space.

The Web site shows the most recent space weather-related messages.

METHOD USED TO ESTIMATE EFFECTIVE DOSE RATES AT FLIGHT ALTITUDES

Basis of SRA System

Primary Solar Proton Spectrum. GOES-10 and GOES-11 proton flux measurements are used to estimate solar radiation dose rates in Earth's atmosphere. They are available from the file transfer protocol (ftp) server of the Space Weather Prediction Center (SWPC) in near real-time and are also available on the Internet (8). The measurements are 5-minute averages and are recorded in several "channels": P4-P7 (15-900 MeV energy, 168-1581 MV rigidity), P10 (510-700 MeV, 1103-1343 MV), and P11 (>700 MeV, >1343 MV). Channels P8 and P9 are excluded from the analysis because their correction algorithms are more complex than those of the other channels, and their exclusion does not significantly affect the calculated dose rates. Fluxes in channels P4-P10 are in terms of differential flux (particles/cm²-steradian-s-MeV). Fluxes in channel P11 are in terms of integral flux (particles/cm²-steradian-s).

In Steps 1-3, fluxes from the SWPC are converted to count rates, galactic background count rates are subtracted, and the count rates are reverted to fluxes using conversion factors that are appropriate for GOES-10 and GOES-11 (9).

In Steps 4-10, the fluxes are used to create a model of the proton flux spectrum entering the atmosphere. The range of rigidities (R) in the model (137-32,545 MV) includes 100% of the flux for over 99% of the solar proton events since the 23 February 1956 event (10). The model consists of six differential flux spectra ($f_i(R)$) in the form of Eq. 1, each spanning an adjoining rigidity range (Table 4). Parameters in Eq. 1 are flux intensity (α) and spectral-hardness index (γ).

$$f_i(R) = \alpha_i R^{-\gamma_i} \quad (\text{Eq. 1})$$

In Step 11, the six spectra are used to calculate effective doses.

Due to the requirement of extrapolating the shape of the proton spectrum in channel P11, the possibility cannot be discounted that the passage of a shock-front with a significantly high flux of protons with rigidities >1343 MV could result in calculated doses rates that are unrealistically high.

Radiation Transport. The Monte Carlo radiation transport code MCNPX 2.6.0 (5) was used to calculate particle fluences (particles/cm²) resulting from the interaction of the exoatmospheric primary protons with the atmosphere. Particles transported with the radiation transport code include protons, neutrons, pions, kaons, photons, electrons, and muons. Previous calculations for altitudes of 60,000 ft and below indicate that fluences of other particles are too small to be of significance in dose calculations (4, 11).

Earth was modeled as a sphere of liquid water of radius 6371 km and density 1 g/cm³. Earth's atmosphere was modeled as 100 spherically symmetric 1-km thick layers of a gaseous mixture of atoms of nitrogen, oxygen, argon, and carbon, in the fractions by weight present in dry air near sea level (12). The density (g/cm³) assigned to each layer was the density at the geometric altitude of the middle of the layer, based on data in NOAA et al. (13). Thus, the thickness of the model atmosphere was 100 km, the area of its uppermost surface was $5.262 \times 10^{18} \text{ cm}^2$, and the total atmospheric depth was 1035.08 g/cm². Empty space surrounded the uppermost atmospheric layer.

Fluence-to-Effective Dose Conversion. Table 1 contains coefficients $\Delta(R, H)$ for estimating effective dose from particle fluences traveling into the top of the atmosphere, specifically primary solar protons. Second-

any particles included in the dose calculations (herein designated as included secondaries) are muons, photons, electrons, positrons, pions, protons, and neutrons. Kaons were not included because their contribution to the total dose was found to be negligible.

For incident solar protons of all energies, values of $\Delta(R, H)$ ($\mu\text{Sv}/(\text{particle}/\text{cm}^2)$) at each rigidity (R) and altitude (H) in Table 1 were calculated as follows:

(a) For each particle included in the dose calculations, the average fluence spectrum at altitude H ($\text{particles}/\text{cm}^2$) per solar proton of rigidity R entering the atmosphere was multiplied by appropriate fluence-to-dose coefficients (6, 14) to obtain average effective dose to an adult per solar proton of rigidity R entering the atmosphere.

(b) Effective doses to an adult were summed to obtain J_D , the average effective dose, in μSv at altitude H , per incident particle of rigidity R entering the atmosphere.

(c) J_D was multiplied by $5.262 \times 10^{18} \text{ cm}^2$ (area of the uppermost surface of the atmosphere) to obtain $\Delta(R, H)$, μSv at altitude H generated by a fluence of 1 $\text{particle}/\text{cm}^2$ of solar protons of rigidity R entering the atmosphere.

A $\Delta(R, H)$ of zero was reported as $1 \times 10^{-16} \mu\text{Sv}/(\text{particle}/\text{cm}^2)$. Coefficients for converting fluence to effective dose were obtained by interpolation from coefficients reported by Pelliccioni (14), but adjusted to meet 2007 ICRP recommendations (6). Table 1 is applicable to any solar particle event.

Calculating Effective Dose Rate at Specific Altitudes

Step 1. The uncorrected flux (ϕ) in each of channels P4, P5, P6, P7, P10, and P11 is reverted to total count rate (galactic plus solar, C) by multiplying ϕ by the conversion factor (k) in Table 2:

$$C = \phi \cdot k \quad (\text{Eq. 2})$$

GOES-10 and GOES-11 have identical instruments and therefore use the same conversion factors.

Step 2. For each channel, the median of the 144 acceptable 5-minute count rates immediately preceding the current 5-minute period is used as an estimate of the galactic cosmic radiation background (B). Count rates are unacceptable if ≤ 0 , designated as "bad" by the archiving source, or if a solar proton event is ongoing (The SEC defines the onset of a solar proton event as the beginning of the first of three or more consecutive 5-minute periods during which the GOES proton flux with energies ≥ 10 MeV exceeds 10 $\text{particles}/(\text{cm}^2 \cdot \text{steradian} \cdot \text{s})$ (15)). The reduction in count rates during a Forbush decrease (16) is small, and solar cosmic radiation doses based on GOES data during a large solar proton event are not appreciably

affected; thus their possible influence is not a concern when calculating galactic cosmic radiation background.

The background corrected count rate (C') is calculated as follows:

(a) Galactic cosmic radiation background count-rate (B) is calculated.

(b) B is subtracted from C , as shown in Eq. 3.

$$C' = C - B \quad (\text{Eq. 3})$$

(c) A negative C' is changed to 1% of B .

Step 3. A differential flux (ϕ'), for each of the channels listed in Step 1, is calculated by dividing the background corrected count-rate (C') by the conversion factor (k') from Table 2:

$$\phi' = C'/k' \quad (\text{Eq. 4})$$

Step 4. With Eq. 5, derived from Eq. 1, preliminary spectral-hardness indices (γ_i) are calculated for differential flux spectra $f_{i=1}(R)$ through $f_{i=5}(R)$, using channel pairs ($P[m]$ and $P[n]$): $i=1$ (channels $P[m=4]$ and $P[n=5]$), $i=2$ ($P[m=5]$ and $P[n=6]$), $i=3$ ($P[m=6]$ and $P[n=7]$), $i=4$ ($P[m=7]$ and $P[n=10]$), $i=5$ ($P[m=10]$ and $P[n=11]$).

$$\gamma_i = \frac{\ln(\phi'_{P[m]}) - \ln(\phi'_{P[n]})}{\ln(R_{P[m]}) - \ln(R_{P[n]})} \quad (\text{Eq. 5})$$

Differential proton fluxes (ϕ'_{P4} through ϕ'_{P11}) were calculated with Eq. 4 in Step 3. Characteristic rigidities ($R_{P[m]}$ and $R_{P[n]}$) for the channels are from Table 2.

Because the γ_i are calculated using Eq. 5, the channel characteristic rigidities are used as the upper and lower rigidity limits of most of the differential flux spectra. Exceptions are the lower rigidities of $f_1(R)$ and $f_6(R)$, and the upper rigidities of $f_5(R)$ and $f_6(R)$. The upper rigidity of $f_5(R)$, which is the lower rigidity of $f_6(R)$, is the lower rigidity limit of fluxes in channel P11. The lower rigidity of $f_1(R)$ is the lowest rigidity of the model. The upper rigidity of $f_6(R)$ is calculated in Step 9. Rigidity limits are in Table 4.

Step 5. Differential fluxes (ϕ) are further corrected (ϕ'') with Eq. 6, using spectral-hardness index correction factors (s) from Table 3. Correction factors are based on γ_i values calculated with Eq. 5. Parameters γ_1 and γ_5 are used with $\phi'_{P[j=4]}$ and $\phi'_{P[j=11]}$, respectively.

$$\phi''_{P[j]} = \phi'_{P[j]} s(\gamma_i) \quad (\text{Eq. 6})$$

For ϕ'_{P5} , ϕ'_{P6} , ϕ'_{P7} , and ϕ'_{P10} , the γ_i values used to calculate $\phi''_{P[j]}$ with Eq. 7 are: for ϕ''_{P5} , γ_1 and γ_2 ; for ϕ''_{P6} , γ_2 and γ_3 ; for ϕ''_{P7} , γ_3 and γ_4 ; for ϕ''_{P10} , γ_4 and γ_5 .

$$\phi''_{P[j]} = \phi'_{P[j]} \left(\frac{s(\gamma_i) + s(\gamma_{i+1})}{2} \right) \quad (\text{Eq. 7})$$

Step 6. For each channel pair in Step 4, the preliminary spectral-hardness index (γ_i) (calculated with Eq. 5) is recalculated with Eq. 5, but substituting $\phi''_{P[m]}$ and $\phi''_{P[n]}$ (calculated with Eq. 6 and Eq. 7) for $\phi'_{P[m]}$ and $\phi'_{P[n]}$. Any negative γ_i is changed to zero. Any γ_i of 1 is changed to 1.000001. For spectrum 6, γ_i is given the value of γ_5 .

Step 7. For each differential spectrum, $f_i(R)$ through $f_5(R)$, α_i is calculated with Eq. 8, using characteristic rigidities ($R_{p[j]}$) from Table 2, differential fluxes ($\phi''_{P[j]}$) from Step 5, and the γ_i from Step 6. For spectra 1, 2, 3, 4, and 5, channel numbers are 4, 5, 6, 7, and 10, respectively.

$$\alpha_i = \phi''_{P[j]} (R_{P[j]})^{\gamma_i} \quad (\text{Eq. 8})$$

For spectrum 6, α_i is given the trial value of α_5 .

Step 8. For channel P11, the integral flux (F_{11}) is obtained by dividing the corrected count-rate calculated in Step 2 (C) by 0.73 (9). If the relationship of Eq. 9 is not satisfied by the trial value of α_6 , then a satisfactory value for α_6 is calculated using Eq. 10.

$$F_{11} \leq \int_{1343 \text{ MV}}^{32,545 \text{ MV}} \alpha R^{-\gamma_6} dR \quad (\text{Eq. 9})$$

$$\alpha_6 = F_{11} (1 - \gamma_6) (32,545^{1-\gamma_6} - 1343^{1-\gamma_6})^{-1} \quad (\text{Eq. 10})$$

The upper limit, 32,545 MV, is the upper rigidity limit of the model and encompasses all the available data for over 99% of the known solar proton events (10). The lower limit, 1343 MV, is the lower rigidity limit of fluxes in channel P11.

Step 9. To find $R_{6,upper}$ (the upper rigidity of $f_6(R)$), the upper limit in Eq. 9 is replaced with 1343 MV and α is set equal to α_6 . The upper limit is then increased in steps of 1 MV until the relationship is satisfied. The resulting $R_{6,upper}$ is also the upper rigidity of fluxes in channel P11 (i.e., $f_6(R > R_{6,upper}) = 0$).

Step 10. At this point, all parameters needed to calculate each $f_i(R)$ have been obtained. To convert each $f_i(R)$ from flux measured at GOES to flux entering the atmosphere, the α_i values calculated in previous sections were each multiplied by π (ref. 11).

Step 11. Effective dose rates ($D(H)$, $\mu\text{Sv/h}$) to an adult, at geopotential altitude (H), from exoatmospheric primary solar protons are calculated with Eq. 11. In Eq. 11: t is a time-scale conversion coefficient ($t = 3600 \text{ s/h}$),

i is the spectrum, $R_{i,upper}$ and $R_{i,lower}$ are rigidity limits of spectrum i in Table 4, $f_i(R)$ represents flux spectra, and $\Delta(R, H)$ represents dose rate per unit of incident proton fluence.

$$D(H) = t \sum_{i=1}^6 \int_{R_{i,lower}}^{R_{i,upper}} f_i(R) \Delta(R, H) dR \quad (\text{Eq. 11})$$

The integral in Eq. 11 is evaluated numerically in 1 MV steps. For integration steps with an upper rigidity less than R_0 (183.5 MV), $\Delta(R, H)$ is set equal to $\Delta(R_0, H)$. For all other integration steps, $\Delta(R, H)$ is set equal to the mean of its values at the upper and lower rigidities of the integration step. The values of $\Delta(R, H)$ at the upper and lower rigidities of the integration step are calculated using linear interpolation of $\ln(R)$ and $\ln(\Delta(R, H))$.

Dose rates ($D(H)$) at altitudes of 30- to 70-thousand feet are estimated by calculating $D(H)$ at each of the nine altitudes in Table 1 with Eq. 11 and then performing a cubic-spline interpolation.

METHOD USED TO ESTIMATE RISK THAT THE EQUIVALENT DOSE TO A CONCEPTUS EXCEEDS 500 μSv IN A 10-HOUR EXPOSURE

The FAA and the National Council on Radiation Protection and Measurements (NCRP) recommend that the equivalent dose to a conceptus not exceed 500 μSv in any month after pregnancy has been declared (1, 17).

Examination of 169 of the 170 solar proton events from January 1986 through May 2008 (18) indicated that 26 events met the criteria for at least one issuance of an SRA (an effective dose $\geq 20 \mu\text{Sv/h}$ at 70,000 ft for at least three consecutive 5-minute periods). Steps 1-9 given above are only appropriate for analyzing GOES data from GOES-8 and more recent satellites (1 March 1995 to present). For solar proton events from 1 January 1986 through 28 February 1995, values of α and γ were estimated from GOES data using the procedure of section A5 in Ref. 11. A total of 42 SRAs would have been issued in the 22-year period. The percentages of these SRAs for which an associated 10-hour cumulative dose to the conceptus exceeded the recommended monthly limit on a polar-latitude flight was 4.8% at 40,000 ft, 21% at 50,000 ft, and 31% at 60,000 ft. Figure 3 shows the risk estimates for 40-, 50-, and 60-thousand feet as a function of effective dose rates at 70,000 ft. For each data point at a specified altitude, the y-coordinate (Y) is a percentage of SRAs,

$$Y = 100 \frac{n}{N} \quad (\text{Eq. 12})$$

where N is the number of SRAs during which the effective dose rate at 70,000 ft equaled or exceeded the x-coordi-

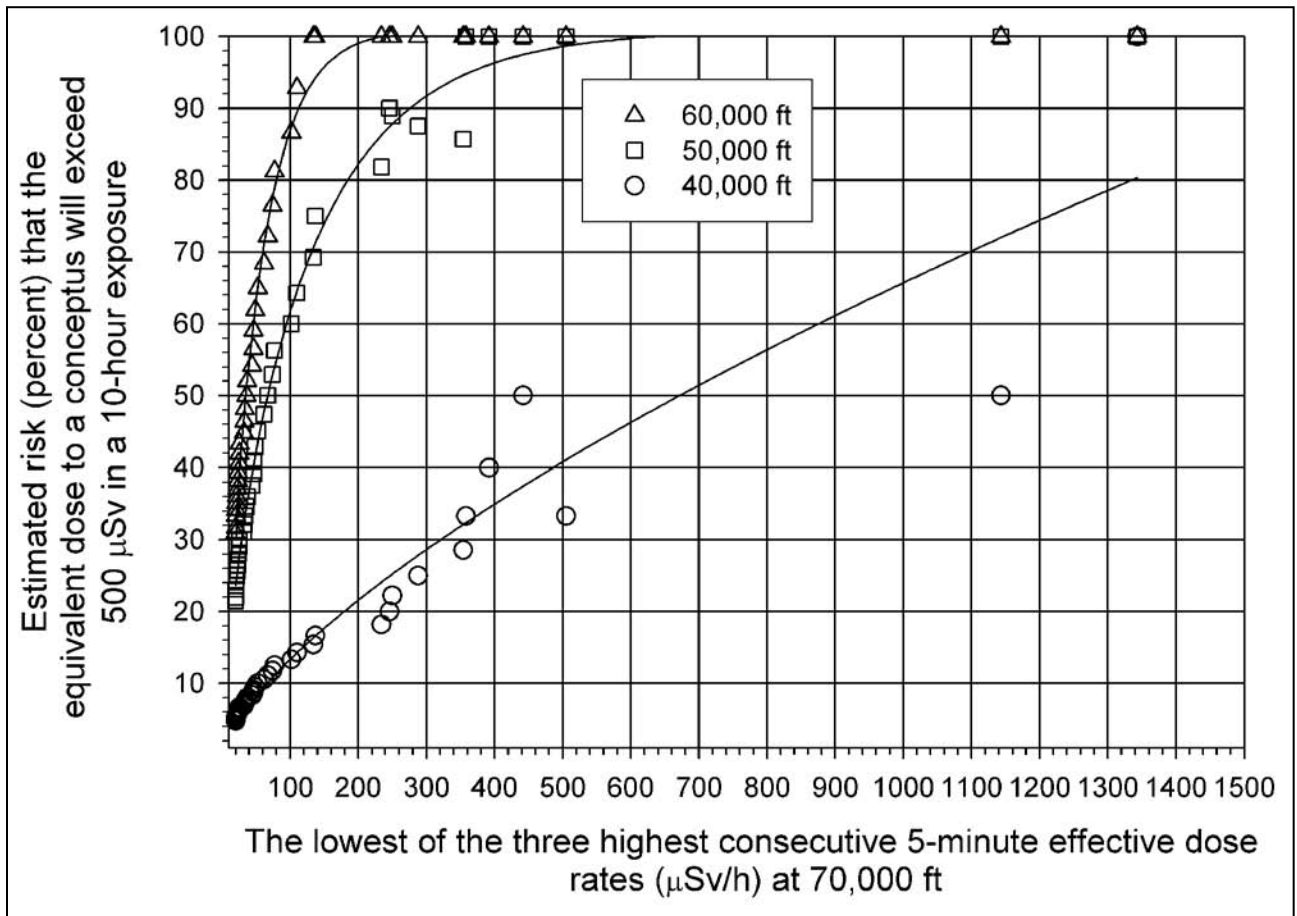


Figure 3. Estimated risk that the equivalent dose to a conceptus in a 10-hour exposure on a polar-latitude flight at 40-, 50-, or 60-thousand feet will exceed 500 μSv when the lowest of the three highest consecutive 5-minute effective dose rates at 70,000 ft reaches the dose rate on the x-axis. Data points are based on examination of past solar proton events since 1986 using effective doses calculated by the method of this report and equivalent doses to the conceptus from Reference 11. For example, the data point at (442, 50) indicates that when the lowest of the three highest 5-minute effective dose rates at 70,000 ft was at least 442 Sv, the equivalent dose to a conceptus at 40,000 ft exceeded 500 μSv in a 10-hour exposure for 50% of alerts.

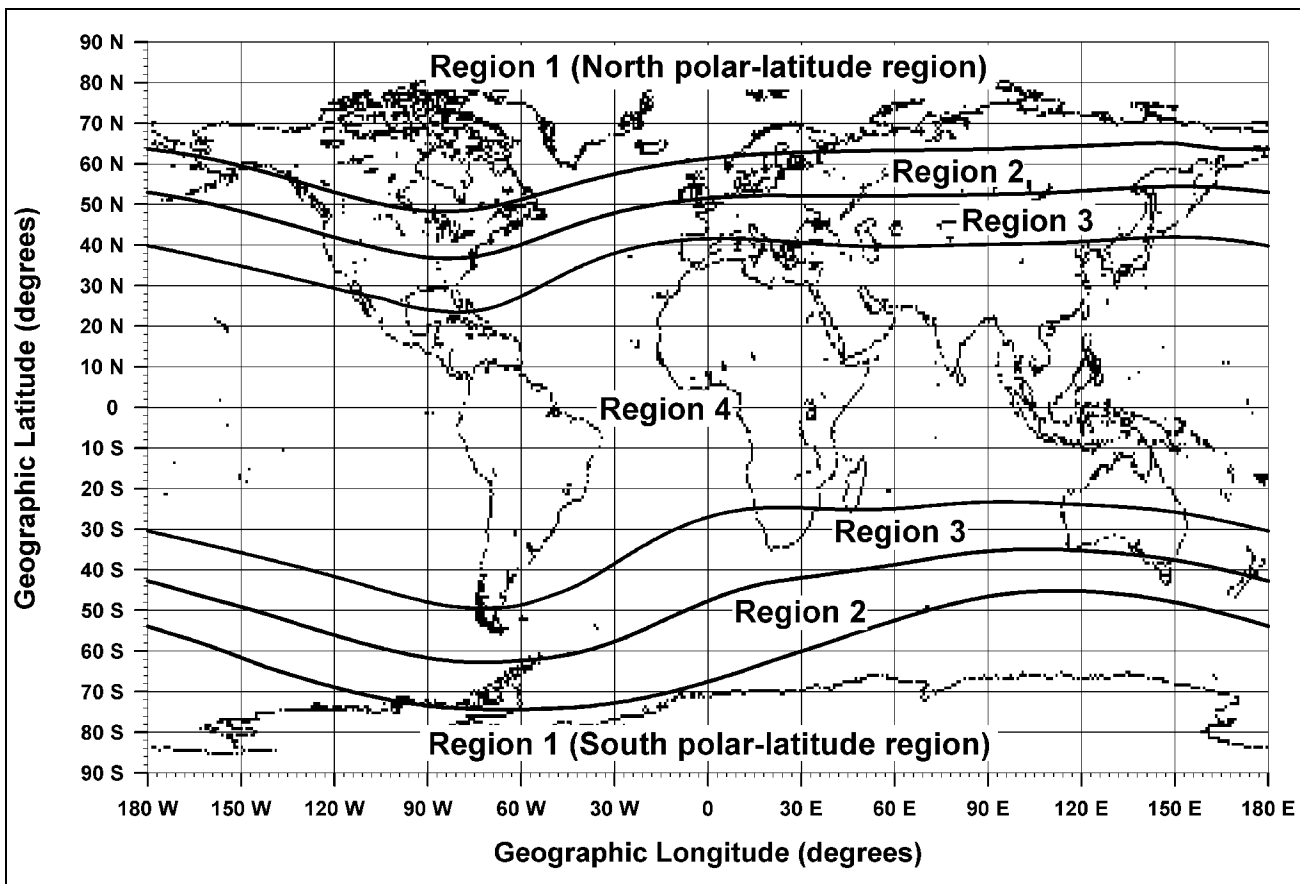


Figure 4. The map is divided into four regions based on the degree of geomagnetic shielding that air travelers are provided by the Earth's magnetic field (23, 24, 25). Region 1 is the polar-latitude region where the magnetic field provides little to no protection from solar cosmic radiation. The highest dose rates occur in Region 1; estimated probabilities that the total dose to the conceptus will exceed the recommended limit are as shown in Figure 3. In the absence of a geomagnetic storm, dose rates in Region 2 will be lower than those in Region 1. During a G5 geomagnetic storm (24), dose rates throughout Region 2 can be as high as those in Region 1. In Region 3, a total dose to the conceptus that exceeds the recommended limit is possible in a 10-hour exposure at 40- to 60-thousand feet (11), but dose rates will always be lower than in Regions 1 and 2. Dose rates in Region 4 never exceed a few percent of dose rates in Region 1. In Region 4, in the period studied, the highest 10-hour dose to the conceptus from solar cosmic radiation at 50,000 ft was <10% of the recommended limit.

nate for three consecutive 5-minute periods and n is the number of the N SRAs for which a 10-hour dose to a conceptus exceeded 500 μSv at the altitude of interest. The risks are estimated using Eq. 13-15, which are fits to the data for 40-, 50-, and 60-thousand feet, where D is the lowest of the three highest consecutive 5-minute effective dose rates at 70,000 ft.

$$\text{Estimated risk at 40,000 ft} = 5.900 (1 - \exp^{-0.00004429 D})^{0.6992} \quad (13)$$

$$\text{Estimated risk at 50,000 ft} = 1.009 (1 - \exp^{-0.0006916 D})^{0.7088} \quad (14)$$

$$\text{Estimated risk at 60,000 ft} = 1.010 (1 - \exp^{-0.01988 D})^{1.016} \quad (15)$$

Dose estimates for the solar proton event of 7 July 1991 could not be reliably estimated because of several gaps in the HEPAD data. However, the peak >10 MeV flux was only 2300 pfu (18) and there was no associated ground level event (19, 20). Of the 169 events examined, 160 had peak >10 MeV fluxes $<10,000$ pfu. There were only 4 of these 160 events during which the 10-hour equivalent dose to the conceptus exceeded the recommended limit and all 4 were associated with very intense ground level events (20). Thus, it is very unlikely that during the 7 July 1991 event the 10-hour equivalent dose to the conceptus exceeded the 500 μSv recommended limit.

RESULTS AND DISCUSSION

Influences not accounted for in the dose rate calculations are: (a) ions other than protons (e.g., alpha particles) in the primary solar particle flux, (b) shielding by Earth's magnetic field, (c) anisotropy in the solar proton flux, and (d) shielding by aircraft structure. In estimating dose rates for the SRA system, only solar protons are used because they are the dominant contributor to the ionizing radiation from the Sun at aircraft flight altitudes and data are available in near real-time. Other radiation information, such as GOES alpha particle measurements and data from the worldwide network of neutron monitors, would enable more complete calculations, including anisotropy effects (21), but not with the immediacy required of an alert system. Earth's magnetic field, including effects of geomagnetic storms, while important at lower latitudes, can be neglected at polar latitudes (Fig. 4). Aircraft structure has very little effect on dose rates. In a study of the solar proton events of 29 September 1989, 14 July 2000, and 16 January 2005, calculations indicated that 0.6 g/cm² of aluminum (approximate "skin" of a Boeing 747) at altitude 40,000 ft changed by $<1\%$ the effective dose of solar plus galactic cosmic radiation. Ferrari et al. (22) investigated the effect of aircraft structure and its contents on the effective dose of galactic cosmic radiation, with a simulated fully-loaded Airbus 340. They found that at a vertical cutoff rigidity of 0.4 GV and altitude

10.7 km (approximately 35,000 ft), aircraft structure and contents reduced the effective dose by 0-8%, depending on location in the aircraft.

Using the method of Reference 11, which incorporates ground-level neutron monitor data and includes dose rates from solar alpha particles, dose rates at 50,000 ft during the seven solar proton events with the highest 10-hour polar-latitude doses at 50,000 ft were calculated. When compared with these, 77% of the dose rates estimated by the method in this report (but using the same fluence-to-dose conversions as Reference 11) were within 20% (mean 5.1% lower, median 5.4% lower, standard deviation 20%), indicating that dose rates generated by the revised SRA system (this report), which uses easily and rapidly available data, are good estimates at aircraft flight-altitudes at polar latitudes.

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APPENDIX A

Sample Solar Radiation Alert System Messages

The following six messages are samples of the messages that would have been issued during the solar proton event that started 16 January 2005, if the revised system had been operational. The samples begin with Test, Service Suspended, and Service Resumed messages that would have been issued on 19 January 2005. Dose rates on 20 January 2005 were high enough to warrant the sending the Alert message, which would have been followed by Alert Update messages until the conditions warranted the issuance of the Alert Cancelled message on 21 January 2005. Numbers in tables are reported to two significant digits.

1. Test

000
WOXX50 KWNP 141506
ALTPAV

Space Weather Message Code: ALTPAV
Serial Number: 9989
Issue Time 2005 Jan 19 1455 UTC

TEST ALERT: Message Delivery Test - Solar Radiation Alert

Comment:

This is a message delivery test of the SOLAR RADIATION ALERT system. Test messages are sent each day at 1500 UTC unless a SOLAR RADIATION ALERT is in progress.

Information on the Solar Radiation Alert system is at
www.faa.gov/education_research/research/med_humanfacs/aeromedical/radiobiology/solarradiation

. . .

CARI users:

heliocentric potential was 583 in December 2004

. . .

Issued by the US DOT, FAA, Civil Aerospace Medical Institute
Send questions to kyle.copeland@faa.gov

2. Service Suspended

000
WOXX50 KWNP 191938
ALTPAV

Space Weather Message Code: ALTPAV
Serial Number: 9990
Issue Time: 2005 Jan 19 1938 UTC

WARNING: GOES Satellite Data Unavailable

Comment:

The Solar Radiation Alert system is currently inactive.

GOES satellite data used in estimating radiation levels at flight altitudes are unavailable. The system will resume normal operation as soon as GOES data become available.

More information at
www.faa.gov/education_research/research/med_humanfacs/aeromedical/radiobiology/solarradiation

Issued by the US DOT, FAA, Civil Aerospace Medical Institute
Send questions to kyle.copeland@faa.gov

3. Service Resumed

000
WOXX50 KWNP 192008
ALTPAV

Space Weather Message Code: ALTPAV
Serial Number: 9991
Issue Time: 2005 Jan 19 2008 UTC

ATTENTION: Satellite Data Now Available

Comment:
GOES satellite data are now available for estimating radiation levels at flight altitudes. SRAS service has resumed.

More information at
www.faa.gov/education_research/research/med_humanfacs/aeromedical/radiobiology/solarradiation

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Send questions to kyle.copeland@faa.gov

4. Alert

000
WOXX50 KWNP 200708
ALTPAV

Space Weather Message Code: ALTPAV
Serial Number: 9992
Issue Time: 2005 Jan 20 0705 UTC

ALERT: Solar Radiation Alert at Flight Altitudes
Conditions Began: 2005 Jan 0650 UTC

Comments:
Satellite measurements indicate unusually high levels of ionizing radiation coming from the Sun. This may lead to excessive radiation doses to air travelers on trans-polar and other high-latitude flights. See map at
www.faa.gov/education_research/research/med_humanfacs/aeromedical/radiobiology/solarradiation

The following dose, dose rate, and risk estimates do not include any shielding by the Earth's magnetic field.

Table 1. Effective dose rate estimates at selected altitudes based on the latest GOES solar proton flux measurements

Altitude (ft)	Effective dose rate (microsieverts/hour)
30,000	40
40,000	160
50,000	450
60,000	890
70,000	1300

Table 2. Effective doses for periods of selected length at selected altitudes*

Altitude (ft)	Effective Dose (microsieverts)			
	Previous 1 hour	Previous 3 hours	Previous 5 hours	Previous 10 hours
30,000	16	16	16	16
40,000	55	55	55	56
50,000	140	140	140	140
60,000	260	260	260	260
70,000	350	350	350	350

*Includes contributions made before the SRA was issued

Table 3. Estimated risk that the equivalent dose to a conceptus in an aircraft at the indicated altitude will exceed 500 microsieverts in a 10 hour exposure.

Altitude (ft)	Risk (%)
40,000	20
50,000	85
60,000	98

To avoid possible excessive radiation exposure to the conceptus, a pregnant aircrew member or passenger may want to avoid flight altitudes of 40,000 ft or more in regions 1-3 shown on the aforementioned map.

Issued by the US DOT, FAA, Civil Aerospace Medical Institute
Send questions to kyle.copeland@faa.gov

5. Update Alert

000

WOXX50 KWNP 200713

ALTPAV

Space Weather Message Code: ALTPAV

Serial Number: 9993

Issue Time: 2005 Jan 20 0710 UTC

UPDATE ALERT: Update for Solar Radiation Alert

Alert Conditions Began: 2005 Jan 20 0650 UTC

Comments:

Satellite measurements indicate unusually high levels of ionizing radiation coming from the Sun. This may lead to excessive radiation doses to air travelers on trans-polar and other high-latitude flights. See map at

www.faa.gov/education_research/research/med_humanfacs/aeromedical/radiobiology/solarradiation

The following dose, dose rate, and risk estimates do not include any shielding by the Earth's magnetic field.

Table 1. Effective dose rate estimates at selected altitudes based on the latest GOES solar proton flux measurements

Altitude (ft)	Effective dose rate (microsieverts/hour)
30,000	51
40,000	200
50,000	590
60,000	1200
70,000	1800

Table 2. Effective doses for periods of selected length at selected altitudes*

Altitude (ft)	Effective Dose (microsieverts)			
	Previous 1 hour	Previous 3 hours	Previous 5 hours	Previous 10 hours
30,000	20	20	20	20
40,000	72	72	72	72
50,000	190	190	190	190
60,000	350	350	350	360
70,000	500	500	500	500

*May include contributions made before the SRA was issued

Table 3. Estimated risk that the equivalent dose to a conceptus in an aircraft at the indicated altitude will exceed 500 microsieverts in a 10 hour exposure.

Altitude (ft)	Risk (%)
40,000	75
50,000	100
60,000	100

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6. Alert Cancelled

000
WOXX50 KWNP 210138
ALTPAV

Space Weather Message Code: ALTPAV
Serial Number: 1008
Issue Time: 2005 Jan 21 0015 UTC

END ALERT: Solar radiation levels not excessive
Alert Conditions Began: 2005 Jan 20 0650
Alert Conditions Ended: 2005 Jan 21 0010

Comment:
The alert issued at 2005 Jan 20 0705 UTC has ended.
The following 2 tables summarize peak effective dose rate estimates and peak effective dose estimates at polar latitudes:

Table 1. Peak effective dose rate estimates at selected altitudes based on the latest GOES solar proton flux measurements

Altitude (ft)	Effective dose Rate (microsieverts/hour)
30,000	130
40,000	460
50,000	1200
60,000	2000
70,000	2700

Table 2. Peak effective doses for periods of selected length at selected altitudes*

Altitude (ft)	Effective Dose (microsieverts)			
	Peak 1 hour	Peak 3 hours	Peak 5 hours	Peak 10 hours
30,000	37	58	67	77
40,000	140	230	270	310
50,000	390	660	790	920
60,000	770	1300	1600	1900
70,000	1100	2000	2500	2900

*May include contributions made before the SRA was issued

Information on the Solar Radiation Alert system is at
www.faa.gov/data_research/research/med_humanfacs/aeromedical/radiobiology/solarradiation

Issued by the US DOT, FAA, Civil Aerospace Medical Institute
 # Send questions to kyle.copeland@faa.gov